The Basic Cardiac MRI Examination: Physical Principles

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The learning objectives for this syllabus contribution are to:

- review the main aspects of patient preparation for cardiac MR and discuss some of the challenges;
- evaluate the trade-offs between temporal and/or spatial resolution and acquisition time in cardiac imaging
- explain the methods used for the assessment of cardiac morphology, function and blood flow;
- summarize the basic techniques used in the evaluation of myocardial perfusion and viability;

Introduction

A basic cardiac MRI examination will incorporate techniques for morphological and functional imaging with more advanced methods used for the evaluation of myocardial viability. Whilst recent developments in hardware and software have substantially improved the quality and reliability of cardiac magnetic resonance (CMR) it is important to understand the methods and their limitations.

The main challenge of CMR is in obtaining diagnostic quality images in the presence of cardiac and respiratory motion. Whilst "real-time" CMR is possible in certain circumstances, the majority of methods rely on ECG synchronisation to address cardiac motion (and to allow for "cine" imaging), whilst various fast imaging techniques are used to reduce the overall acquisition time to a breath-hold. It should be noted that only part, i.e., a segment, of the full MRI raw data acquisition is performed in each heartbeat. The final reconstructed images therefore contain raw data segments from multiple heartbeats. Ideally the patient needs to have a reproducible cardiac cycle over the acquisition period. The MRI system will provide arrhythmia rejection whereby a segment falling outside of an acceptance window will be rejected and reacquired.

Obtaining a good quality ECG from inside the bore of an MRI system is challenged by the magneto-hydrodynamic effect. This is due to blood, a conducting fluid, moving through a static magnetic field and thereby generating an additional voltage that gets superimposed on the ECG. Since the peak flow velocity occurs around the time of ventricular repolarisation, this effect manifests as an increase in the T-wave amplitude. This may lead to the system sometimes erroneously triggering on

the T-wave rather that the R-wave. The development of vector cardiogram (VCG) gating in an attempt to mitigate this effect has improved the reliability of triggering. It is also important to ensure proper skin/electrode preparation through the use of specialised, mildly abrasive, gels to reduce skin impedance.

Whilst the pros and cons around the choice of field strength for CMR are beyond the scope of this article it is reasonable to advocate the use of dedicated cardiac coil arrays with high channel counts. Such coils allow the application of parallel imaging techniques, which can be used to reduce overall acquisition times, without substantially affecting image quality.

Morphological Imaging

Morphological images ideally demonstrate a particular myocardial contrast weighting e.g. T1w, or T2w, with ideally no signal from the blood pool. In order to obtain images in a breath-hold a fast spin echo (FSE) based method is used with the VCG-triggered echo-train readout positioned in diastole when cardiac motion is reduced. Since blood within the ventricle may appear with variable signal intensity a double inversion recovery (DIR) preparation scheme is often used to suppress the signal from blood. This comprises a non-selective 180° pulse to invert all the tissue, including blood, within the imaging volume. This is immediately followed by a slice-selective -180° pulse to de-invert the tissue to be imaged, whilst blood outside of this slice will remain inverted. During the inversion time (TI) inverted blood will recover due to T_1 relaxation and will also flow into the imaging slice. The FSE readout is performed when blood's longitudinal magnetisation crosses zero, thereby resulting in a morphological image with a dark blood pool. Either all or a segment of the raw data can be acquired in each heartbeat depending upon the clinical needs. Trade-offs with overall acquisition time can then be made with respect to contrast weighting, spatial resolution and slice coverage.

Functional Imaging

Functional images ideally demonstrate myocardial motion throughout the cardiac cycle thereby allowing both qualitative and quantitative assessment of global and regional ventricular and valvular function. Multiple images, known as temporal phases, are acquired throughout the cardiac cycle, so that when played back as a movie or "cine" loop the motion can be clearly shown. The basic sequence is a balanced steady-state-free-precession (bSSFP) gradient echo that has high blood/myocardial contrast. The bSSFP sequence has a very short repetition time (TR) so a segment of raw data can be acquired in a single heart-beat for each temporal phase. The size of each segment will dictate the duration of each of the temporal phases, i.e. the overall cine frame-rate, and the

overall acquisition time. Images are usually acquired in multiple planes to illustrate the tissue motion. If multiple cine images covering the left and/or right ventricles are acquired then the epicardial and endocardial borders can be outlined and both global and regional metrics of function can be determined.

MRI also has the ability to encode the velocity of tissue, usually blood flow, within the phase of the MR signal. Special cine phase-contrast (CPC) imaging sequences allow multi-phase imaging of blood flow. The gray-scale in each temporal phase is proportional to velocity, which allows the measurement of peak velocities in the case of valvular stenosis. In addition, since the cross-sectional area of a vessel can be easily measured, it is possible to quantify the volume of blood flow and hence, for example, regurgitant fractions.

Myocardial Perfusion

MRI offers a number of advantages over the conventional nuclear medicine methods for the evaluation of myocardial perfusion, including improved spatial resolution, the absence of overlying tissue attenuation effects as well as an absence of ionizing radiation. Clinical myocardial perfusion MRI involves imaging the heart during the bolus administration of a gadolinium-based contrast agent[1], during which we observe a transient 'T_1-enhancement' effect whereby the myocardial signal intensity increase during the passage of the contrast agent through the myocardium. Regions of ischaemia with poor perfusion will show a significantly reduced and/or delayed enhancement compared to the normally perfused regions.

Since the first pass of the contrast agent through the myocardium is very rapid, typically 10 s or less, the imaging requirements are extremely demanding. Ideally we would like to get whole heart coverage with a temporal resolution of one heartbeat, however we can realistically only achieve 3-4 slices per heartbeat. The basic sequence is therefore a very short TR gradient echo sequence with an acquisition time of less than 200ms. A non-selective 90° saturation pulse is applied prior to the imaging sequence which increases the sensitivity for changing T_1s. The saturation pulse also provides a degree of arrhythmia insensitivity to allow for any differential signal recovery if the heart rate varies. Care must be taken in viewing perfusion images to ensure that apparent perfusion 'defects', particularly those in the subendocardium, are not actually due to susceptibility effects from the high concentration of contrast agent in the left ventricle during the first pass, or motion artifacts due to the myocardium moving during the readout period.

[1] At present gadolinium-enhanced MRI of the heart is an off-label use for all FDA approved gadolinium-based contrast agents (GCBAs).

Myocardial Viability

One way to identify viable myocardium is to perform cine imaging whilst increasing the dose of a pharmacological agent such as dobutamine which increases myocardial contractility. Any myocardial tissue with a wall motion abnormality at rest and which subsequently improves with low-dose dobutamine is regarded as viable. Further increases in the dobutamine dose results in the myocardium becoming ischemic and ceasing to contract.

An alternative and extremely powerful approach is the direct imaging of nonviable myocardial regions using Late Gadolinium Enhancement (LGE). Recent evidence shows that LGE is exclusively related to irreversible injury, irrespective of contractile function or age of injury. After either an acute ischemic injury or a chronic infarction there is an increase in the extracellular volume which results in retention of a standard extracellular gadolinium contrast agent. In acute infarcts the loss of cell membrane activity allows the contrast agent to accumulate in the extracellular space, whilst in chronic infarcts the cardiomyocytes are replaced by fibrotic tissue that has a smaller intracellular space compared to the extracellular space. If T_1w imaging is performed 10-20 minutes following administration of the contrast agent there is maximal signal difference between infarcted and normal myocardium.

To maximise visualisation of the infarct the imaging sequence of choice is an inversion-recovery prepared gradient echo acquisition in which the inversion time (TI) is optimised to null the signal from normal myocardium. Optimising the TI can be somewhat tricky and various approaches have been developed over the years. Firstly rapid, low spatial resolution, LGE images can be obtained at different TIs to visually assess which results in the minimal signal in normal myocardium. Secondly, TI 'scout' sequences have been developed which employ a single inversion pulse followed by multiple low spatial resolution gradient echo readouts, each effectively acquired at an increasing TI. Finally sequences that retain the sign of the inverted magnetisation, so-called Phase Sensitive Inversion Recovery (PSIR) have been developed. PSIR images maintain good normal/infarcted tissue contrast over a wider range of TIs than the magnitude-reconstructed standard IR sequences.

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